DESIGN OF METAL STRUCTURES IN THE SOVIET UNION

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The consructional shape of a structure is determined by the combination of the main constituent parts and elements, such as the beams, girders, trusses, columns or shells that form this structure. The best constructional shape of a structure and its elements is selected in the process of designing, a creative process in which many solutions may be derived. The duty of the designer in each case is to determine the most appropriate and rational solution for his designing problems in confirmity with the modern level of development of science and engineering. This article presents the methods of design and analysis of metal engineering structures (of steel and aluminium) in the Soviet Union.

Methods of analysing metal members

The theory applied for analysis of the structures and their members and elements is that relating to the strength of materials and structural mechanics. The main purpose of this theory is that of determining the internal stresses induced in members under the action of applied loads.

Previously, steel structures in the Soviet Union were studied by means of the method of elastic design, based upon allowable stresses. Currently, a more precise method of analysis has been introduced, the method of limit design, formulated by Soviet scientists under the leadership of Professor N. Streletsky. These principles underlie "Building Standards and Regulations" published in the USSR, Part II [1] of which is devoted to the designing of structural members and foundations. For a number of structures (bridges, hydraulic engineering structures, blast furnaces, and so on) special recommendations and instructions are prepared to ensure a design that reflects the specific condition of their form of service. In this method of design, each member is considered in its limiting state. The limiting state of a member denotes a state such that it no longer meets the service requirements, that is, either it loses its ability to withstand external loads, or it acquires an inadmissible deformation or local damage.

Two limiting states have been established for metal members, viz.

a) the first limiting state, also known as the condition of non-destruction, determined by the load-carrying capacity (Strength stability or endurance). The requirements of this state must be met by all metal members,

b) the second limiting state, determined by the development of excessive deformations (deflections and displacements). This state is used for checking members in which the magnitude of the deformations may limit the possibility of their service.

The first limiting state is expressed by the inequality

$$N < \phi \qquad (1)$$

where N = design force in a member induced by the combined action of all design loads P in their most unfavourable combination, and

ϕ = load-carrying capacity of the member, which is a function of the geometrical dimensions of the member and the design strength of the material R.

The design load is determined as the product of the service load P_s [2], and a load factor n, which takes into account the danger of an increase in load over its service value by reason of possible load changes,

$$P = P_s n$$

In general, the load factor has been established for the dead load as $n_q = 1.1$, and for a live load $n_p = 1.2 - 1.4$ [2]. The right-hand term of the basic inequality (1), the load-carrying capacity of a member ϕ, depends upon the ultimate strength of the material, i.e., both its resistance to the action of the various forces, characterised by the mechanical properties of the material, and termed the service resistance or strength R_s, and upon the geometrical characteristics of the cross section (section area F, section modulus W, etc.).

For structural steels, the service tensile, compressive and bending strengths are assumed equal to the minimum value of the yield point guaranteed by corresponding USSR State Standards (GOST), i.e.

$$R_s = \sigma_y$$

The service tensile, compressive and bending strengths of aluminium alloys are assumed equal to the smaller of the following two quantities:

1. Seven-tenths of the minimum guaranteed value of the ultimate tensile strength, i.e., 0.7 σ_u.
2. The arbitrary yield point, also known as the offset stress $\sigma_{y\ 0.2}$, corresponding to the stress that produces a unit perma-

nent elongation of 0.2 %.

The design strength R is derived by multiplication of the service strength by a homogeneity factor K_{hom} (less than unity), that takes into account the danger of a reduction in the strength of the material is comparison with its service strength by reason of possible variations in the mechanical properties of the material 3 :

$$R = K_{hom} R_s$$

For ordinary carbon steels, the factor K_{hom} = 0.9, for high-quality (low-alloy) steels and for aluminium alloys K_{hom} = 0.85, and for heat-treated steels K_{hom} = 0.8. The design strength R is accordingly a stress equal to the lowest possible value of the yield point (or the ultimate tensile strength) of a material, which is taken as the limiting strength of the member. To ensure the safety of a structure, account must be taken of possible deviations from the normal service conditions, together with special features of the work performed by the member (for example, the particularly heavy working conditions of girders that support certain types of overhead cranes; a corroding medium inducing an increased rate of metal corrosion; constant work of the members at the limit loads, with no more than slight variations, and when a high degree of probability exists that the stresses produced by these loads will coincide with the lowest value of the strength of the material).

To ensure that due account is taken of all these circumstances, there is introduced a safety factor, known as the factor of service conditions of structural members and their elements m, which reduces the value of the design strength when necessary; thus we have

$$R = K_{hom}\, m\, R_s$$

Consequently, in the design, for instance, of crane girders for overhead cranes subjected to heavy service conditions, such as those encountered in iron and steel workshops, a factor for service conditions of $m = 0.9$ is introduced, while in the designing a tank working under conditions of practically constant load produced by the material filling it (with a small load factor), the values assigned to the service condition factor is usually 0.72 to 0.80. In all cases when the design strength is determined in accordance with the ultimate tensile strength (and not the yield point), the design strength is additionally corrected by a factor that takes into consideration the service conditions of the material in the member (less than unity), and allowing for uneven distribution of the stresses when the material is working beyond the yield point.

In conclusion, the values of the design strengths for riveted and bolted connections are corrected by a factor of connection service conditions that allows for both the kind and nature of behaviour of the connection, and the quality of the holes.

The values of the two factors last mentioned are contained in the Building Standards and Regulations [1]. Thus the limiting condition (1) for checking the strength can now be expressed as

$$N \leq FR \quad \text{or} \quad M \leq WR$$

where N and M are the design axial forces and bending moments induced by the design loads (with respect to load factors n).

The basic formulae for checking the strength of members under design will consequently assume the following form

$$\sigma = \frac{N}{F_n} \leq R \quad \text{or} \quad \sigma = \frac{M}{W_n} \leq R \tag{2}$$

where σ = design stress in element (induced by design loads)

F_n = net area of section (holes subtracted)

W_n = net section modulus

R = design strength of material, taken from the Building Standards and Regulations.

The second limiting state of a member characterised by the appearance of excess deformations (deflections) requires that that member possess adequate stiffness. Under conditions of normal service, the magnitude of the unit strain ($\frac{\delta}{h} = \frac{\text{deflection}}{\text{span}}$ or $\frac{\delta}{h} = \frac{\text{deflection}}{\text{depth}}$) must not exceed the value of the tolerated unit strain ($\frac{1}{r_o}$) established by the standards for various members. Thus the condition should be observed that $\frac{\sigma}{L} < \frac{1}{r_o}$.

In determination of the deformation (deflection), the service load, and not the design load, is applied, i.e., no attention is paid to the load factors. Steel members directly subjected to repeated moving loads in buildings and structures with heavy working conditions (such as the crane girders of steel foundries), as well as members directly subjected to a regular vibrating load, must be analysed for endurance.

The endurance of members subjected to variable loads depends to a considerable degree upon the shape of the member, and the related uneven destribution of the force lines inducing a concentration of stresses which facilitates brittle failure. In investigation of the endurance of steel members, the design strengths are reduced by the introduction of a factor derived from the expression

$$\gamma = \frac{1}{(aK_e \pm b) - (aK_e \mp b)K_{rs}}$$

Here, a and b = coefficients dependent upon the kind of structural member

K_e = effective stress concentration factor, which is the ratio of the fatigue limit for a smooth flat specimen to that of a specimen with the given stress concentration

K_{rs} $= \frac{\sigma_{min}}{\sigma_{max}}$ = range ratio of stress cycle, where σ_{min} and σ_{max} are the minimum and maximum absolute values of the stresses in the element under study, measured (each with its own sign) from the design load level.

The working expressions for checking the endurance will accordingly assume the following form

$$\sigma = \frac{N_s}{F} \leqslant \gamma R \quad \text{or} \quad \sigma = \frac{M_s}{W} \leqslant \gamma R,$$

in which N_s and M_s are the force and moment, respectively, determined from the service loads without the application of any load factors. The Building Standards and Regulations allow for account to be taken of the development of plastic strains for simple rolled beams (I beams and channels), constrained to prevent buckling, and carrying a static load. In this instance, the values of the plastic section moduli are taken as equal to $W_p = 1.12\ W_e$ for bending in the plane of the web, and $W_p = 1.2\ W_e$ for bending parallel to the flanges to reduce the edge strains. The Building Standards and Regulations further allow of account to be taken of the development of plastic strains for constantsection welded beams with a ratio between the width of the compressed flange overhang and the flange thickness of $\frac{b}{t} \leqslant 10$, and a ratio between the depth of the web and its thickness of $\frac{h}{t} \leqslant 80$ (for steel 3). At spots with the greatest bending moment, large shearing stresses are not tolerated. They should comply with the inequality $\tau \leqslant 0.3\,R$.

When a long zone of pure bending is present, the corresponding section modulus, with a view to the avoidance of excessive strains, is taken as equal to half the sum of the elastic and plastic moduli, viz., $0.5(W_e + W_p)$. In continuous beams, the formation of plastic hinges is taken as the limiting state, but on the condition that the system remains unchanged.

In the analysis of continuous beams (rolled and welded) that comply with all the limitations indicated above for simple beams, the Building Standards and Regulations allow of the design of bending moments, to be determined upon the basis of equalisation of the support and the span moments (provided that the adjacent spans do not differ by more than 20 %).

In this instance, the values of the design moment are taken as equal to:

1) In continuous beams with freely supported ends - the greater of the two values $M = \frac{M_{01}}{1 + D/L}$ or $M = \frac{1}{2} M_{02}$

in which M_{01} and M_{02} = maximum bending moments in extreme and intermediate spans respectively, computed in the same way as for a freely-supported simple beam

D = distance to the extreme support from the section corresponding to moment M_{01}

L = extreme span

2) In simple and continuous beams with fixed ends,

$$M = 0.5\ M_o$$

where M_o is the greatest value of the moments calculated for a beam with pinned supports.

In all cases in which the design moments are determined on the assumption of plastic strains developing (equalisation of the moments), the beam strength should be checked in accordance with formula $\sigma_x = \pm \frac{M}{W_x}$, and application of the elastic section modulus. In analysis beams made from aluminium alloys, the development of plastic strains is omitted from consideration.

Comparison of the method of limit design with that of allowable stress design

When designing is based upon allowable stresses, the member is considered in its working state under the action of the loads tolerated in the normal service of the structure, viz. the working or service loads. The allowable stresses are equivalent to a definite fraction of the ultimate stress of the material, which for structural steel is taken as being equal to the yield point σ_y. The main formulae for checking the strength of structural members are

$$\sigma = \frac{N_s}{F_n} \leqslant \sigma' = \frac{\sigma_y}{f} \quad \text{or} \quad \sigma = \frac{M_s}{W_n} \leqslant \sigma' = \frac{\sigma_y}{f} \qquad (3)$$

where N_s, M_s = axial forces and bending moments induced by the service loads

σ' = allowable stress established by the corresponding standards and regulations

σ_y = yield point of steel

f = safety factor

The safety factor has been introduced here, in view of possible deviations of the actual load from the theoretical one, and the actual design of the member from the scheme applied in analysis. It also covers variations in the mechanical properties of the material. These possible deviations are allowed for by the safety factor, which relates the design assumptions to the actial behaviour of the member in service.

On comparison of the new method of limit design with the old one of allowable stress design (expressions (2) and (3)) it is observable that the procedures of analysis are identical, although in the first case the stresses in the member are obtained from the design loads (with account taken of the load factors). These stresses are compared with the design strength, whereas in the second case the stresses are calculated from the service loads, and compared with the allowable stresses.

The main distinguishing feature of the new method of analysis lies in the member being considered not in its working state, but in a limit state. This calls for more precise formulation of the limiting conditions that lead to failure of the member, along with studies of the nature of the safety factor. This was the reason that led to replacement of a single general safety factor f by three differentiated ones, n, K_{hom} and m. Members designed on the basis of allowable stresses, with a single safety factor regardless of the different service conditions and the different effect of the loads (their changeability), have in fact different margins of safety.

The introduction of three factors, the most important of which is the load factor n, enables appraised not only of the absolute values of the loads, but also the influence of their ratio. This results in the apprearance of structures with all their members possessing equal strength in the resistance of service loads. The new procedure unifies the methods of analysis and design; it is based upon physical parameters. It makes it practicable to consider, in a simpler way, not only the elastic, but also the elastoplastic phase of work of the material. The loads and the homogeneity factors obey the statistical laws of distribution and can be controlled.

The weights of the structures are calculated by the standards and regulations applied in different countries

Table 1.

Country	Trusses	Columns	Girders
USSR	100	100	100
USA	117	118	107
England	116	112	102
Germany	104	103	95
Belgium	111	121	107
Poland	100	104	103

Loads: with respect to the duration of their action, loads are divided into:

1. Permanent or dead loads - such as the dead weight of the structural members, the weight of floors, roofs, walls, the weight and pressure of soils, and so on.

2. Temporary or live loads acting for a long period, and known as movable loads - including the weight of stationary equipment, the loads imposed upon the floors of stores and warehouses, libraries, theatres; the pressure of gases, liquids and loose materials in tanks and reservoirs; the continuous thermal action of equipment.

3. Live loads acting for a short time, and known as moving loads - such as cranes and other mechanical handing equipment, the load of the occupants of buildings, wind loads, temperature (climatic) action, erection and so on.

4. Special loads - including loads caused by earthquakes, accidents,

the settlement of foundations, and so on.

As a rule, not one, but various combinations of loads act upon a structure. The probability that the maximum loads of all kinds will act simultaneously on a structure is very small, and a structure designed for such a combination of loads would have an excessive margin of safety.

The Building Standards and Regulations provide for the following three categories of load combinations:

1. main combinations, consisting of the dead loads, movable loads and one, most important, moving load;
2. additional combinations, consisting of the dead loads, movable loads and all the moving loads;
3. special combinations, consisting of the dead loads, movable loads, possible moving loads, and the special loads.

In the consideration of these combinations, the vertical and horizontal loads induced by overhead cranes are treated as one moving load.

In exceptional cases, the main combination also takes into account the combined action of a snow load and one or two overhead cranes (except for cranes with a "regime" of light and medium duties).

In the design of members with account being taken of the additional load combinations, the values of the design live loads (or of the stresses in the members that correspond to them) should be multiplied by a load combination factor c = 0.9: when account of is taken of special combinations, a factor c = 0.8 should be employed.

For special structures (bridges, hydraulic engineering structures, special cranes, etc.) the loads and their combinations are established by special statements.

As a rule, the weight of the steel structural members themselves is no more than a small fraction of the total load, and can be established as a preliminary measure by means of an approximate estimate, or from similar existing structures.

The service live loads are obtainable from various building standards and codes. The wind load is considered not only as the result of active pressure upon the windward wall, but also as a product of the suction acting upon the roof and the inner side of the opposite wall.

With dynamic loads that create impact, and induce vibrations in a structure (cranes, trains), the same service loads are used in analysis, but are subsequently multiplied not only by the usual load factor, but by a special dynamic load factor.

Materials used in metal members

The main structural steel is of the low-carbon type, obtained by the open-hearth or the new converter process, rimming, killed or semi-killed (see Table 2). Its distinguishing properties are poor hardening, high plasticity and good weldability.

These three kinds of steel are utilised in welded members in the following ways:

1. Killed steel (cп) in members designed for a service temperature below -30 deg C, and also (regardless of the service temperature) in members that work under especially exacting conditions - under dynamic and vibrating loads.
2. Semi-killed steel (пс) - in the main load - bearing members of roofings and ceilings (trusses, frame collar-beams, beams).
3. Rimmed steel (кп) - in the remaining instances.

Table 2. Mechanical properties of structural steel.

Kind of steel		Grade of steel	Thickness of rolled stock mm	Yield point kg/mm²	Ultimate tensile strength kg/mm²	Longitudinal strain, per cent, at least	Impact strength kg m/cm² at t=°C	Design strength kg/mm²	ASTM
Low-carbon steel	C-24	BMCm3CП BKCm3CП	1,2,3 1)	24-22	38-47	23-21	t=20°C 7-10	21	A7 A36 A373
		BMCm3ПC BKCm3ПC	1,2,3	24-22	38-47	23-21			
		BMCm3KП BKCm3KП	1,2,3	24-21	38-47	23-21			
		Cm3Mocт	-	24	38	24-22	t=20°C 8-10		
		M16C		23	38	24-22			
	C 30	MCmT	6-40	30	44	22	t=-40°C 3,5		
Low alloy		09Г2	4-32	31-30	45	18			A242 A440 A441 V42
		14Г2	4-32	34-33	47-46	18	t=-40°C		
		10Г2C1	4-40	38-34	52-48	18	3-5	29	V45
		15ГФ	4-32	38-34	52-48	18			V50
		15XCHD	4-32	35	50	18			
		10XCHD	4-40	40	54-52	16		34	
High strength steels	C 45	18Г2AФ	4-60	45	55	18	t=-40°C 4,5		V55
		18Г2AT	4-60	45	55	18	4,5		
	C 50	15XCHD	10-32	50	60	16	4,0		V60
		15Г2CФ	8-32	50	60	16	4,0		V65
Heat-treated steels	C 60	15XГ2CФP	4-20	60	70	12	3,0		A514
		14XГC	8-20	60	70	12	3,0		
	C 75	15XГ2CMФP	8-32	75	85	10	3,0		
		14ГCФP	8-20	75	85	10	3,0		

1) Note: The rolled stock thickness groups are established as follows:
1st group - section steel (angles, ribs, bars) - up to 40 mm inclusive; steel shapes (I beams, channels) - up to 15 mm inclusive; in web thickness; sheets and wide strips - from 4 to 20 mm inclusive.
2nd group - section steel - over 40 to 100 mm; shapes over 15 to 20 mm, sheets and wide strips - over 20 to 40 mm.
3rd group - section steel - over 100 to 250 mm; shapes - over 20 mm, sheets and wide strips - over 40 to 60 mm.

Low-alloy steels are supplied in conformity with GOST 5058-65, and special specifications, and are utilized in the main heavy members, and in members that are subjected to low temperature. The designation of low-alloy steel grades, consisting of letters and members, mainly characterizes the chemical composition of the steel. The left-hand figures indicate the average carbon content in hundredths of a per cent, and the letters after these figures denote the constituents, viz., Г for mangenese, C for silicon, X for chromium, H for nickel, D for copper, T for titanium, M for molybdenum, etc.

The use of low-alloy steels leads to a reduction of about 15 % in the weight of the members, although the cost is almost the same. Considerably greater economy of steel in structural members is obtainable by the use of heat-treated low-alloy or low-carbon steels, in which the yield point and the ultimate strength are appreciably higher, with a very slight reduction in plasticity. Heat treatment consists in heating the steel to a temperature of 900 - 930 deg C (above the upper critical point) and hardening (quenching) in water with or without subsequent tempering.

Heat-treated steels of grades C 30, C 45, C 60 and C 75 will soon be available (here the figure indicates the lowest value of the yield point of the steel). The introduction in the near future of other types of heat-treated steels, which will conduce to a great reduction in the weight of members, and a general saving in costs of about 25 - 30 %, will be of major significance.

Aluminium alloys

Aluminium alloys are divided into the cast types, used in machine building, and malleable or forged types (worked under pressure - in presses, by extrusion, rolling, stamping, etc.) used in constructional work.

These alloys are provided with the strength required either by addition of the appropriate components, or by mechanical action, consisting in cold deformation of the billets - cold working (cold hardening, drawing); for some of the alloys, heat treatment (hardening, ageling, etc.) is applied. The alloys are designated as follows, in accordance with the alloying elements:

AMr denotes aluminium - magnesium alloys (in the grade designation AMr6, the figure 6 indicates that the alloy contains about six per cent of magnesium);

AMЦ denotes an aluminium - manganese alloy;

AB (Avial) and AD are alloys of aluminium with magnesium and silicon;

D1, D16, etc. denote duralumin (the figure indicates the number of alloy); the basic components of these alloys are aluminium, magnesium and copper;

B indicates high-strength alloys (B65, B92 and others) mainly consisting of aluminium, magnesium, copper and zinc.

These alloys are more costly.

Alloys denoted by the letters AD correspond to aluminium (A) malleable (D) alloys of an international standard. The figures following the letters indicate the number of the alloy (AD31, AD33).

The state in which the material is supplied is also denotes by letters: M refers to annealed (soft) material, T - hardened and naturally aged (T1 - artificially aged), H - cold worked,   - semi-cold worked.

The strength of the alloys can be increased from 1.3 to 1.5 times by heat-treatment, but this will be accompanied by a reduction in the unit elongation. Duralumin, Avial and high-strength alloys are strengthened by heat treatment. Grade D16 - T duralumin is a strong alloy, recommended for riveted structural members, but is difficult to weld, since annealing of the weld zone accurs; this sometimes leads to crack formation. Duralumin has less resistance to corrosion.

The heart-treated alloys AB and AD are usable for welded members, provided that welding is followed by heat treatment; this is necessary to increase the strength of the weld, since after welding this strength will be about 60 % of that of the basic metal. Alloys AMr and AMЦ are not strengthened by heat treatment. Alloys AMr6 and AD33, by reason of their good welding ability and relatively good mechanical properties, have found the widest use in welded members: they have comparatively high resistance to corrosion. Alloy AMy is low in strength, has high resistance to corrosion, can be welded, and is comparatively cheap. It is usable for enclosures and guards. Table 3 lists the mechanical properties of some alluminium alloys.

Table 3. Mechanical properties of aluminium alloys.

Grade of alloys	State on delivery	Ultimate strength kg/mm²	Yield point kg/mm²	Longitudinal strain %	Ultimate shearing strength kg/mm²	Endurance limit kg/mm²	Brinell hardness number Bhn kg/mm²
D1	D1-T	36	22	12			
D16	D16-T	40-49	30	10	28		105
	D16-M	21	11	18	13		42
AB	AB-T1	33	28	10	20	9,8	95
	AB-M	15	-	20		4,5	30
B92	B92T	36	20	20			
AMr6	AMr6-M	32	16	15			70
AMy	AMy-M	13	5	20		5,5	30
	AMy-	16	13	16		6,5	40

Field of application and the nomenclature of metal structural members

Steel structural members have found the widest use in the following types of structures, divisible into two groups.

A. Framework or skeleton systems, with their main elements beams, girders, trusses, and columns, including:

1) the framework of industrial buildings and structures (mainly iron-and-steel workshops and machine-building plants, with internal members such as crane girders, platforms, and so on
2) railway, highway and urban long-span bridges
3) civil multi-storey buildings, exhibition pavilions, various vaults, roofs, floors and domes
4) special-purpose buildings, including hangars and shipbuilding slips
5) special structures, for example towers and masts, headworks of mines, oil derricks, hydraulic engineering structures, trestle cranes, etc.

B. Shell systems, largely composed of plates or sheets, and including:

1) gas-holders, and tanks for the storage and distribution of gases
2) tanks and reservoirs for liquid storage
3) bins and bunkers for the storage and handling of loose materials
4) special structures such as blast furnaces, air heaters, gas scrubbers
5) large-diameter piping employed in iron-and-steel, coke and by-product works, hydroelectic power plants, oil and gas pipelines.

By virtue of their low specific weight and high resistance to corrosion, structural members made from aluminium alloys have found their primary use in enclosing members such as roof cladding, wall panels, window sashes, etc., and also in the chemical and petroleum industries. Aluminium members are employed in structures in which the weight of the structure itself is of considerable importance (transfer cranes, drawbridges, large-span roofs of pavilions, structures erected in seismic areas, and in regions difficult of access).

References

[1] ChuП II-B 3-62 "Steel structures. Building standards and Regulations"

[2] CHuП II A 11-62 "Loads"

[3] CHuП III A 10-62 "Structural members and Foundations. Basic Prescriptions for Designing"